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Evaluation of organ doses following prostate treatment with permanent brachytherapy seeds: A Geant4 Monte Carlo simulation study

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Abstract

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Evaluation of organ doses following prostate treatment with permanent brachytherapy seeds: a Geant4 Monte Carlo simulation study

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Abstract. This study aimed to evaluate the absorbed doses received by the organs at risk (OARs) following prostate treatment with permanent Iodine-125 (^{125}I) brachytherapy seeds. In order to simulate an enlarged abnormal prostate due to malignancy, the MIRD5 adult male anthropomorphic phantom (readily available in the Geant4 Monte Carlo package) was modified by increasing the prostate volume to 35 cm^3. The permanent seeds were constructed with an outer cylindrical dimension of 4.5 mm (length) × 0.8 mm (diameter). The effects of various activity per seed (0.5, 0.6 and 0.8 mCi), number of seeds (62, 78, 94 and 110 seeds) and radionuclides, i.e. Palladium-103 (^{103}Pd), ^{125}I and Cesium-131 (^{131}Cs), towards the absorbed dose to the OARs (i.e. rectum, urinary bladder and both testicles) were investigated. In this study, prostate dose of up to 237 Gy was simulated, which resulted in 11 Gy dose to rectum, 7 Gy to urinary bladder and 4 Gy to each testicle. The doses were considered as reasonable, given the low dose rate nature of the treatment, allowing tissue repair for the OARs. Optimal seeds arrangement was found to consist of 78 or fewer seeds, as it resulted in the lowest dose to the OARs. For similar prostate dose, ^{103}Pd resulted in the lowest dose to the OARs, followed by ^{125}I and ^{131}Cs. Permanent seed brachytherapy allows high dose to be delivered to the prostate, while ensuring minimal dose to the OARs.

1. Introduction

Permanent prostate brachytherapy is a renowned and common treatment option for the management of early-stage prostate cancer. Commonly used radionuclides include Iodine-125 (^{125}I) ($\bar{E}$ = 28 keV, half-life, $t_{1/2}$ = 60.0 d), Palladium-103 (^{103}Pd) ($\bar{E}$ = 21 keV, $t_{1/2}$ = 17.0 d) and Cesium-131 (^{131}Cs) ($\bar{E}$ = 29 keV, $t_{1/2}$ = 9.7 d). Instead of other alternatives, such as external beam radiotherapy (EBRT) or radical prostatectomy, this treatment is often preferred due to perceived advantages over urinary, bowel and sexual functions [1]. Although serious morbidity is rare, proctitis has been reported in 1–9 % of the patients [2], while urethral strictures, incontinence and prolonged irritative symptoms may also occur.

The estimations of dose to the organs at risk (OARs), i.e. urinary bladder, rectum and both testicles, are therefore crucial in preparation for any possible complications. However, direct dose measurements may not be possible, without involving invasive procedure. Furthermore, placing dosimeters onto the organs will be challenging as not all dosimeters are size-appropriate and suitable to be placed onto wet surfaces, as it can affect the device performance. Handheld dosimeter may be useful to estimate the dose at the patient's skin surface, while dose estimation for other OARs will not be feasible.

Monte Carlo (MC) radiation simulation has been increasingly used for dosimetric assessment of internal organs following radiation treatment [3]. Geant4 is one of the newest MC code packages, which provides accurate probability estimation of radiation events, with flexible geometric manipulation for various purposes, especially in medical physics. In this study, the effects of different activity per seed, number of seeds, and radionuclide source used, towards the dose received by the OARs were evaluated using the Geant4 package.

2. Methodology

2.1. *The MIRD5 phantom*

The study was performed using Geant4.10.0.p03 [4, 5] advanced example *human_phantom*. The 70 kg phantom was adopted from MIRD Pamphlet 5, with a height of 174 cm [6]. Male phantom was selected, which was equipped with male genitalia and testicles, however, without the presence of a prostate. Thus, an oval shaped prostate was created, and positioned inferior to the urinary bladder (Figure 1a). The prostate volume was set to 35 cm^3, which represents an enlarged prostate due to malignancy [7].

In the example, the rectum was initially combined with the sigmoid and ascending colons as the 'lower large intestine (LLI)'. However, for this study, the rectum was separated from the LLI, by creating a separate cylinder with a volume of 70 cm^3 [8]. The rectum was positioned posterior to the prostate (Figure 1b).

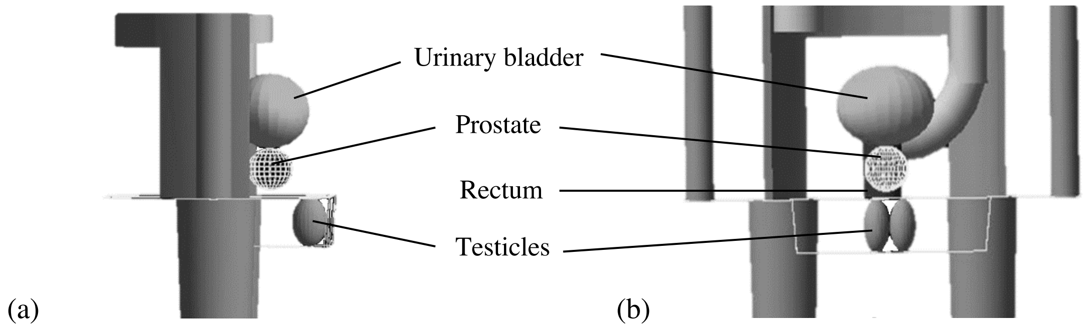

Figure 1. The (a) lateral and (b) frontal views of the MIRD5 phantom's pelvic region showing the urinary bladder, prostate, testicles and rectum.

2.2. *Designs of permanent seeds*

2.2.1. *^{125}I seed.*

The seed was constructed based on ADVANTAGE™ ^{125}I (IAI-125A, IsoAid L.L.C., Port Richey, FL), with ^{125}I as the radioactive source. The seed has an outer dimension of 0.8 mm (diameter, *d*) × 4.5 mm (length, *l*) [9, 10], as shown in Figure 2. The seed contains a 3 mm silver rod (10.5 g.cm^{-3}) with *d* of 0.5 mm, fully coated with a 1 μm active layer (AgI containing the ^{125}I). The thickness of titanium casing (4.54 g.cm^{-3}) is 0.05 mm.

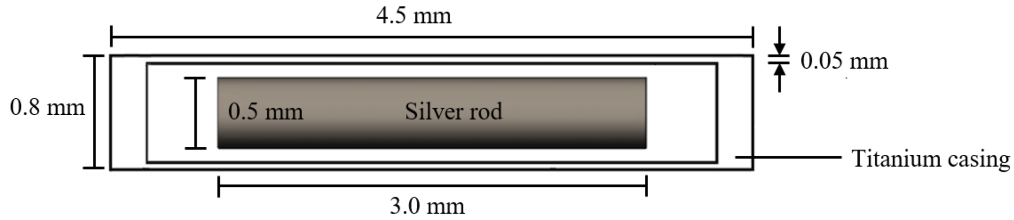

Figure 2. The ADVANTAGE™ ^{125}I seed as constructed using the Geant4 code.

2.2.2. ^{103}Pd seed. The seed was constructed based on TheraSeed® (200, Theragenics Co., Buford, GA), with ^{103}Pd as the radioactive source. The seed (Figure 3) has similar outer dimension as the ^{125}I seed [11]. It consists of two cylindrical graphite pellets (2.27 g.cm^{-3}), coated with ^{103}Pd and separated by a cylindrical lead marker (11.34 g.cm^{-3}). Each graphite pellet has a dimension of 0.56 mm (d) × 0.89 mm (l), while the lead marker is 0.51 mm (d) × 1.09 mm (l). The ^{103}Pd coating is 2.2 μm thick, while the thickness of titanium casing is 0.056 mm. The active length is 4.23 mm (two graphite pellets and lead marker), calculated using the TG-43 effective line source length approximation [9].

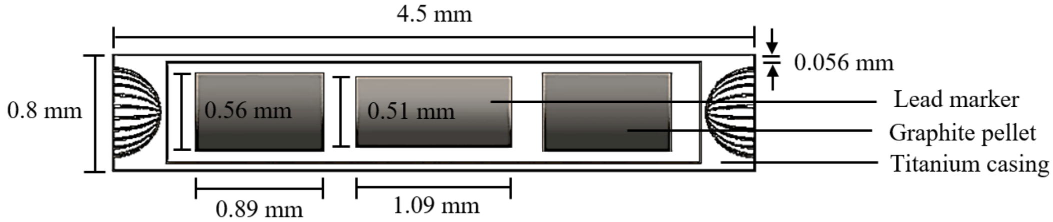

Figure 3. The TheraSeed® ^{103}Pd seed as constructed using the Geant4 code.

2.2.3. ^{131}Cs seed. The seed was constructed based on Proxcelan® (CS-1 Rev2, IsoRay Medical Inc., Richland, WA), with ^{131}Cs as the radioactive source. The outer dimension of the seed is also similar as the ^{103}Pd and ^{125}I seeds [12]. The seed (Figure 4) consists of a 0.25 mm (d) × 4.0 mm (l) gold marker (19.3 g.cm^{-3}), which is housed in a 0.62 mm (outer d) (0.4 mm inner d) × 4.0 mm (l) Pyrex/ceramic tube (2.4 g.cm^{-3}). The inner surface of the tube is coated with 0.05 mm layer of ^{131}Cs. The housing containing the marker is placed in a titanium capsule with 0.1 mm thickness. The void within the capsule is filled with argon gas. The corresponding active length is 4.0 mm [9].

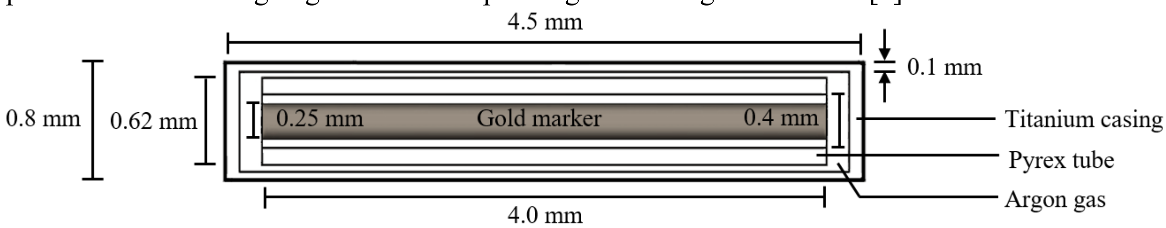

Figure 4. The Proxcelan® ^{131}Cs seed as constructed using the Geant4 code.

2.3. Effects of different treatment parameters on the absorbed dose.
The Low Energy Electromagnetic Package [13], based on the Livermore Evaluated Data Libraries, was adopted to model the electromagnetic interactions of photons and electrons. The threshold of production of secondary particles was fixed to 1 mm. The Geant4 Radioactive Decay component was used to model the decay of the radionuclides.

The seeds were uniformly arranged and placed inside the prostate as shown in Figure 5c. Uniform loading allows all the seeds to be arranged between constant distances, for each x, y and z-axes. This resulted in the placement of 94 seeds within the prostate, which was used as the default arrangement setup for this study.

For every setup, 10^7 disintegrations were generated and repeated three times, to obtain a standard deviation of less than 1 %. The mean energy (MeV) deposited to each OARs was normalized to the energy deposited to the prostate. These normalized values were used to obtain the absorbed dose to all the OARs, by multiplying the values with the dose prescribed to the prostate, i.e. 145 Gy.

2.3.1. Different activity per seed. For this purpose, only the ^{125}I seed was used, with no specific prescribed dose. Using the default setup, the activity for each seed was set to 0.49 mCi. The common activity per seed used in a permanent ^{125}I prostate implant is in the range of 0.3 to 0.8 mCi [14]. The simulation was later repeated by changing the activity per seed to 0.6 and 0.8 mCi. The seeds were allowed for full decay and the resulting absorbed dose to the prostate and OARs were recorded.

2.3.2. Different number of seeds. For this purpose, again only the ^{125}I seed was used. Different number of seeds, i.e. 62, 78, 94 and 110, [15] arranged in the prostate were simulated. The prescribed dose to the prostate was maintained to 145 Gy, and the absorbed dose received by the OARs were compared between these arrangements. Since the consensus on the optimal seed distribution does not exist [14], the classic approach, which is the uniform loading was used to space the seeds with uniform distances. The placement of 62, 78, 94 and 110 seeds are shown in Figure 5a, b, c and d.

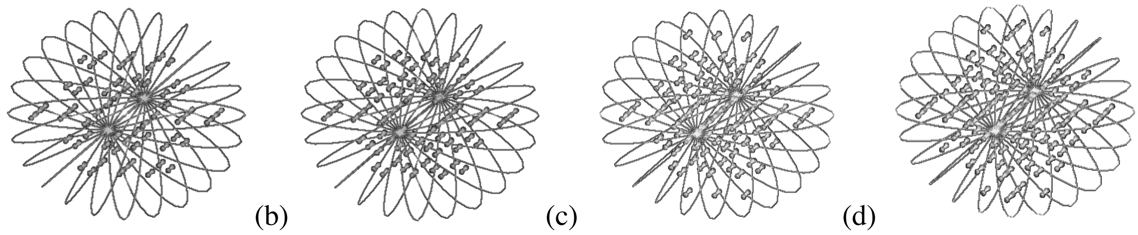
(a) (b) (c) (d)

Figure 5. The placements of (a) 62, (b) 78, (c) 94, and (d) 110 ^{125}I seeds within the prostate volume (seen in wireframe mode).

2.3.3. Different radionuclides. By using the 94 seed arrangement, the simulation was later repeated using the ^{103}Pd and ^{131}Cs seeds. The prescribed dose to the prostate was set to 145 Gy, and the absorbed dose received by the OARs were compared between these radionuclides.

3. Results & Discussions

3.1. Different activity per seed
For 94 seeds configuration, the activity per seed of 0.49 mCi resulted in 145 Gy to the prostate, which is the recommended prescribed dose for permanent brachytherapy using the ^{125}I seed. The activity per seed of 0.6 and 0.8 mCi resulted in the absorbed dose to prostate of 177 and 236 Gy, respectively. The absorbed dose to the OARs for different ^{125}I activity per seed used are shown in Figure 6.

The rectum was observed to receive the highest dose, followed by urinary bladder and the testicles (up to 11, 7 and 4 Gy, respectively, when the 0.8 mCi per seed was used). In general, the dose for each organ increased as the activity per seed increased. Although the maximum activity per seed was used, the dose to the OARs did not exceed the dose limits for permanent prostate implant, i.e. 90 Gy for rectum [14], 20 Gy for testicles [16] and 70 Gy for urinary bladder [17].

3.2. Different number of seeds
The number of seeds used were 62, 78, 94 and 110, where the activity per seed was adjusted so the dose prescribed to the prostate was fixed to 145 Gy. The absorbed dose to the OARs for different number of seeds are shown in Figure 7. The rectum was observed to receive the highest dose, followed by urinary bladder and the testicles, for all the number of seeds used. The absorbed dose to OARs for 78 seeds configuration was found to be the lowest, followed by 62, 94, and 110 seeds.

The absorbed dose to OARs for 78 seeds were found to be lower than the 62 seeds configuration due to its lower activity per seed. However, as the number of seed increases beyond 78, the seeds need to be placed closer to the prostate edge, hence resulted in a higher dose to OARs, although the activity per seed is lower as the number of seeds increased.

3.3. Different radionuclides

^{103}Pd resulted in the lowest absorbed dose to OARs, followed by ^{125}I and ^{131}Cs (Figure 8), due to limited penetration of the emitted radiation energies, hence allowing high dose to be prescribed to the prostate, while sparing the surrounding healthy tissues [18].

On the other hand, ^{131}Cs emits slightly higher energy compared to the other sources, hence, the radiation can escape from the source organ and deposits energy to the surrounding organs. However, ^{131}Cs provides a higher dose rate, which can be beneficial in terms of the duration of treatment. The relatively shorter $t_{1/2}$ of ^{131}Cs (only 7.9 d) allows shorter radiation exposure for the patient's family and the surrounding environment [18].

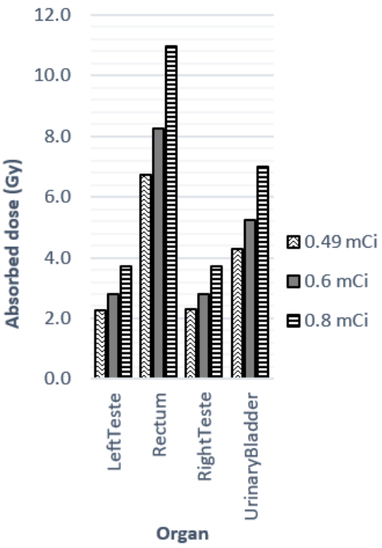

Figure 6. The absorbed dose to OARs with different ^{125}I activity per seed.

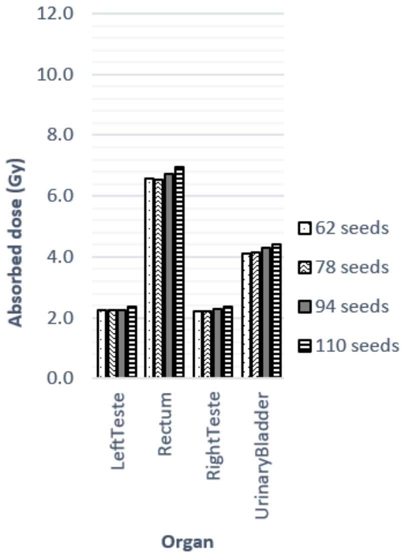

Figure 7. The absorbed dose to OARs with different number of seeds.

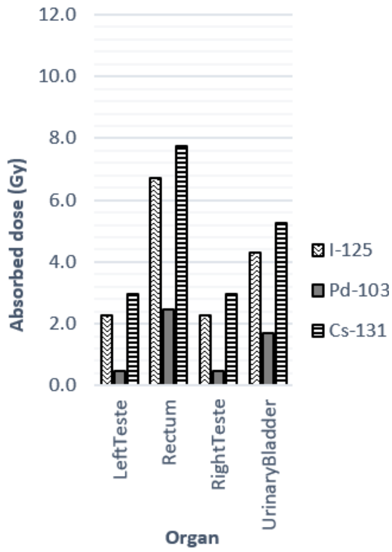

Figure 8. The absorbed dose to OARs with different radionuclides.

4. Conclusion

The maximum prostate dose of up to 237 Gy was simulated, which resulted in 11 Gy dose to rectum, 7 Gy to urinary bladder and 4 Gy to each testicle. These doses were considered as reasonable, given the low dose rate nature of the treatment, allowing tissue repair for the OARs. Optimal seeds arrangement was found to consist of 78 or fewer seeds, as it resulted in the lowest absorbed dose to the OARs. For similar prostate dose, ^{103}Pd resulted in the lowest absorbed dose to the OARs, followed by ^{125}I and ^{131}Cs. Even though ^{131}Cs resulted in the highest dose to the OARs, the dose to the prostate can be delivered faster than the other isotopes, due to its shorter $t_{1/2}$.

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